

High Intensity Beam Operation of the Brookhaven AGS*

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Abstract. For the last few years the Brookhaven AGS has operated at record proton intensities. This high beam intensity allowed for the simultaneous operation of several high precision rare kaon decay experiments. The record beam intensities were achieved after the AGS Booster was commissioned and a transition jump system, a powerful transverse damper, and an rf upgrade in the AGS were completed. The intensity is presently limited by space charge effects at both Booster and AGS injection and transverse instabilities in the AGS.

THE AGS ACCELERATOR COMPLEX

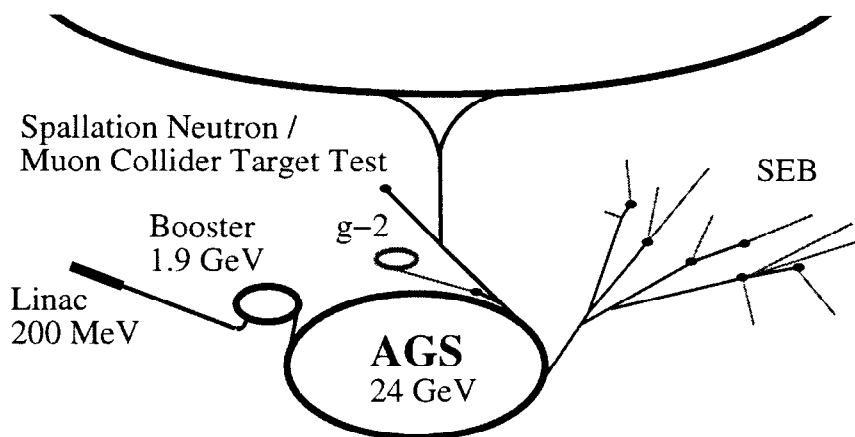


FIGURE 1. The AGS-RHIC accelerator complex.

Fig. 1 shows the present layout of the AGS-RHIC accelerator complex. The high intensity proton beam of the AGS is used both for the slow-extracted-beam (SEB) area with many target station to produce secondary beams and the fast-extracted-beam (FEB) line used for the production of muons for the g-2 experiment and for

*) Work performed under the auspices of the U.S. Department of Energy

AGS Proton Intensity History

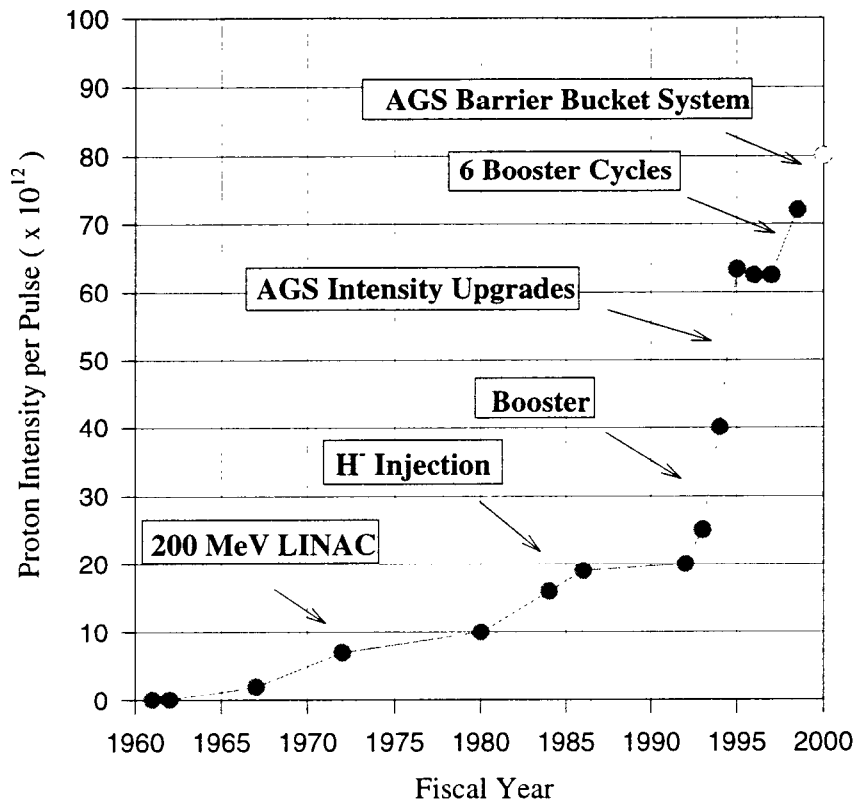


FIGURE 2. The history of the evolution of the proton beam intensity in the Brookhaven AGS.

high intensity target testing for the spallation neutron sources and muon production targets for the muon collider. The same FEB line will also be used for the transfer of beam to RHIC.

The proton beam intensity in the AGS has increased steadily over the 40 year existence of the AGS, but the most dramatic increase occurred over the last few years with the addition of the new AGS Booster. In Fig. 2 the history of the AGS intensity improvements is shown and the major upgrades are indicated. The AGS Booster has one quarter the circumference of the AGS and therefore allows four Booster beam pulses to be stacked in the AGS at an injection energy of 1.5 – 1.9 GeV. At this increased energy, space charge forces are much reduced and this in turn allows for the dramatic increase in the AGS beam intensity.

HIGH INTENSITY OPERATION OF THE LINAC AND BOOSTER

The 200 MeV LINAC is being used both for the injection into the Booster as well as an isotope production facility. A recent upgrade of the LINAC rf system made it possible to operate at an average H^- current of $150\ \mu A$ and a maximum of $12 \times 10^{13}\ H^-$ per $500\ \mu s$ LINAC pulse for the isotope production target. Typical beam currents during the $500\ \mu s$ pulse are about $80\ mA$ at the source, $60\ mA$ after the $750\ keV$ RFQ, $38\ mA$ after the first LINAC tank ($10\ MeV$), and $37\ mA$ at end of the LINAC at $200\ MeV$. The normalized beam emittance is about $2\ \pi\ mm\ mrad$ for 95 % of the beam and the beam energy spread is about $\pm 1.2\ MeV$. A magnetic fast chopper installed at $750\ keV$ allows the shaping of the beam injected into the Booster to avoid excessive beam loss.

The achieved beam intensity in the Booster surpassed the design goal of 1.5×10^{13} protons per pulse and reached a peak value of 2.3×10^{13} protons per pulse. This was achieved by very carefully correcting all the important nonlinear orbit resonances especially at the injection energy of $200\ MeV$ and by using the extra set of rf cavities that were installed for heavy ion operation as a second harmonic rf system. The second harmonic rf system allows for the creation of a flattened rf bucket which gives longer bunches with lower space charge forces. The fundamental rf system operated with $90\ kV$ and the secondary harmonic with $30\ kV$. The typical bunch area was about $1.5\ eVs$. Even with the second harmonic rf system the incoherent space charge tune shift can reach one unit right at injection (3×10^{13} protons, norm. 95 % emittance: $50\ \pi\ mm\ mrad$, bunching factor: 0.5). Of course, such a large tune shift is not sustainable, but the beam emittance growth and beam loss can be minimized by accelerating rapidly during and after injection. Best conditions are achieved by ramping the main field during injection with $3\ T/s$ increasing to $9\ T/s$ after about $10\ ms$. The quite large non-linear fields from eddy currents in the Iconel vacuum chamber of the Booster are passively corrected using correction windings on the vacuum chamber that are driven by backleg windings [1].

Recently the Booster rf system was modified to allow for the acceleration of a single bunch. At this lower frequency $45\ kV$ was available for the first harmonic and $22\ kV$ for the second harmonic. This results in the same available total bucket area. With only one bunch in the Booster a peak intensity of about 1.8×10^{13} was reached. Single bunch operation in the Booster allowed for the transfer of six Booster loads into the AGS reducing the need for very high intensity in the Booster. Nevertheless, the lower peak intensity was a surprise which was eventually traced to the factor of two lower synchrotron frequency. During the approximately $250\ \mu s$ long H^- injection period the synchrotron motion is now not providing enough dilution and high peak line densities are developing. More elaborate longitudinal painting schemes were studied which may eventually result in higher intensity even with single bunch operation.

AGS HIGH INTENSITY OPERATION

The AGS itself also had to be upgraded to be able to cope with the higher beam intensity. During beam injection from the Booster, which cycles with a repetition rate of 7.5 Hz , the AGS needs to store the already transferred beam bunches for about 0.4 seconds. During this time the beam is exposed to the strong image forces from the vacuum chamber which causes beam loss from resistive wall coupled bunch beam instabilities within as short a time as a few hundred revolutions. An example of such an instability for relatively low beam intensity is shown in Fig. 3. Even though the eight bunches individually show a rather complicated growth pattern of the vertical displacement a Fourier analysis shows that the coupled bunch modes develop as expected for a resistive wall instability with the lowest frequency mode growing the fastest.

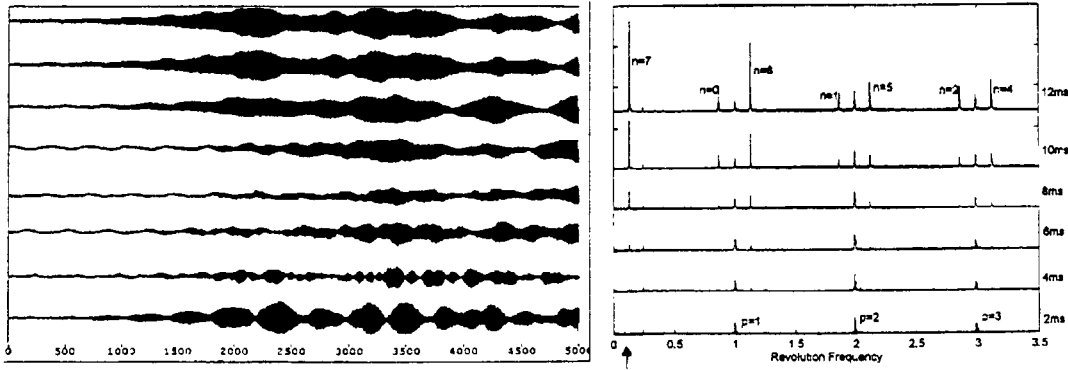


FIGURE 3. The left figure shows the growth of a vertical coupled bunch instability at AGS injection energy of 1.5 GeV for the eight bunches. The horizontal scale is in turns. The right graph shows the evolution of the frequency components during the growth of the instability.

A very powerful feedback system was installed that senses any transverse movement of the beam and compensates with a correcting kick. This transverse damper can deliver $\pm 160\text{ V}$ to a pair of $50\ \Omega$, one-meter-long strip-lines. A recursive digital notch filter is used in the feed-back circuit to allow for accurate determination of the average beam position and increased sensitivity to the unstable coherent beam motion. This filter design is particular important for the betatron tune setting of about 8.9 which is required to avoid non-linear octupole stopband resonance at 8.75. With an incoherent tune shift at the AGS injection energy of 0.1 to 0.2 it is still necessary, however, to correct the octupole stopband resonances to avoid excessive beam loss.

To reduce the space charge forces further the beam bunches in the AGS are lengthened by purposely mismatching the bunch-to-bucket transfer from the Booster and then smooth the bunch distribution using a high frequency 100 MHz dilution cavity. The resulting reduction of the peak current helps both with coupled bunch instabilities and stopband beam losses. Fig. 4 shows the evolution of a mismatched bunch being diluted.

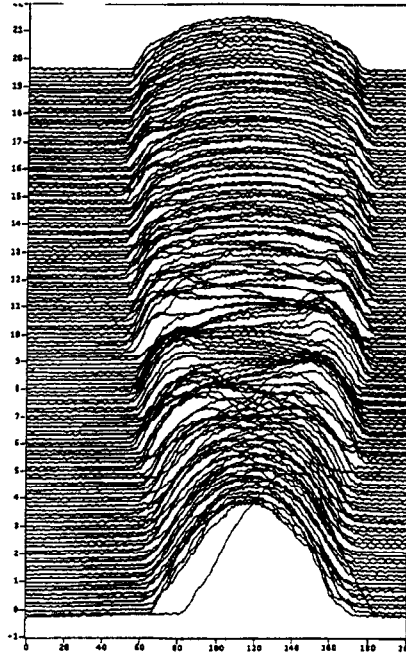


FIGURE 4. Evolution of a mismatched bunch at AGS injection under the influence of the 100 MHz dilution cavity. The traces show the intensity of the same bunch every revolution. The horizontal scale is in nanoseconds

A large part of the injection losses at the AGS are due to a relative slow loss during the first millisecond the transferred bunches circulate in the AGS. No direct cause for this loss could be identified but it is correlated with a sustained transverse coherent beam oscillation shown in Fig. 5. The coherent oscillations result from miss-matched beam injection to blow-up the transverse emittance and therefore reduce the space charge tune shift. Although the coherence persists over a whole millisecond the middle part of the beam bunch has a coherent space charge tune shift of about 0.1 and therefore very high frequency vertical modulations appear. The bunch intensity is about 1.3×10^{13} protons.

At bunch intensities above 1.3×10^{13} protons a vertical head-tail instability develops with a single bunch in the AGS. Fig. 6 shows both the bunch shape as well as the vertical modulation. The modulation develops towards the tail of the bunch and is very asymmetric. The growth rate of about 50 ms is quite slow consistent with a weak head-tail instability. However, the observed asymmetry suggests a very short wake or possibly an electron-proton instability. The instability can be cured by changing the vertical tune.

The large space charge forces during AGS injection can be mitigated by maintaining a practically debunched beam during the AGS injection process. To accomplish this, cavities that produce isolated rf buckets can be used to maintain an empty gap for injection of additional Booster beam pulses. Isolated bucket cavities, also called Barrier Bucket cavities, have been used elsewhere [3]. However, for this stacking

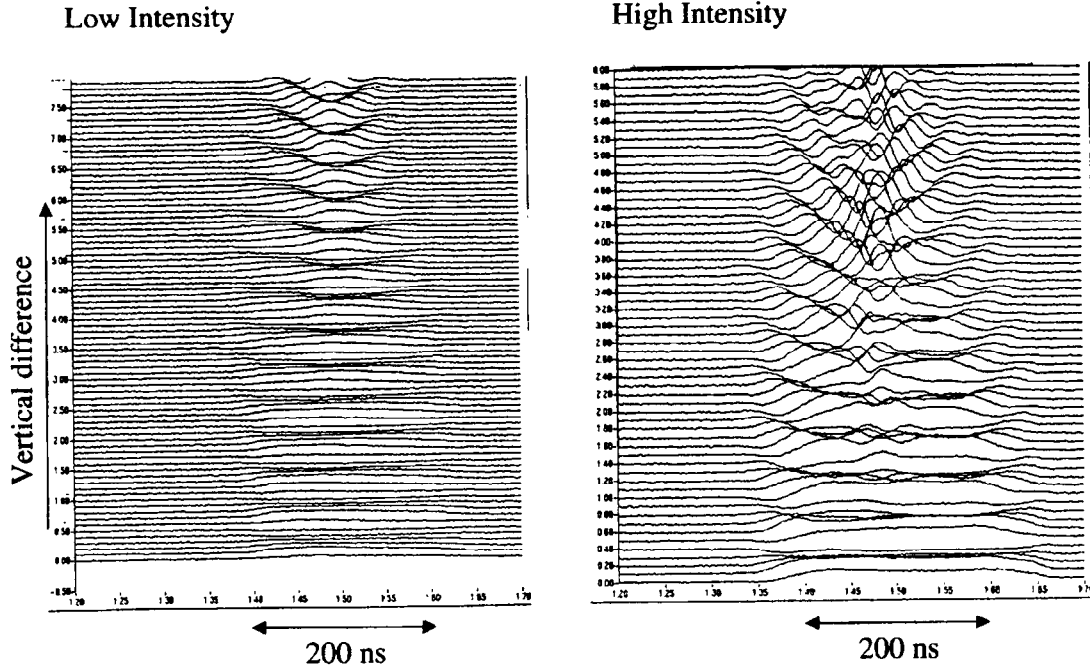


FIGURE 5. Evolution of the vertical miss-match at AGS injection. The traces show the vertical displacement of the same bunch every revolution. The horizontal scale is in microseconds

scheme, a high rf voltage will be needed to contain the large bunch area of the high intensity beam. A successful test of this scheme has recently been completed using two 40 kV Barrier cavities [4].

During acceleration the AGS beam has to pass through the transition energy after which the revolution time of higher energy protons becomes longer than for the lower energy protons. This potentially unstable point during the acceleration cycle was crossed very quickly with a new powerful transition energy jump system with only minimal losses even at the highest intensities [2]. The large lattice distortions introduced by the jump system prior to the transition crossing severely limits the available aperture of the AGS in particular for momentum spread. Efforts to correct the distortions using sextupoles have been partially successful. After the transition energy, a very rapid, high frequency instability developed which could only be avoided by purposely further increasing the bunch length using again the high frequency dilution cavity.

The peak beam intensity reached at the AGS extraction energy of 24 GeV was 7.2×10^{13} protons per pulse also exceeding the design goal for this latest round of intensity upgrades. It also represents a world record beam intensity for a proton synchrotron. Individual bunches with an intensity of 1.2×10^{13} had a bunch area of about 3 eVs at AGS injection but were diluted to about 10 eVs during acceleration.

At maximum beam intensity about 30 percent of the beam is lost at Booster injection (200 MeV), 20 percent at injection into the AGS (1.9 GeV), which includes

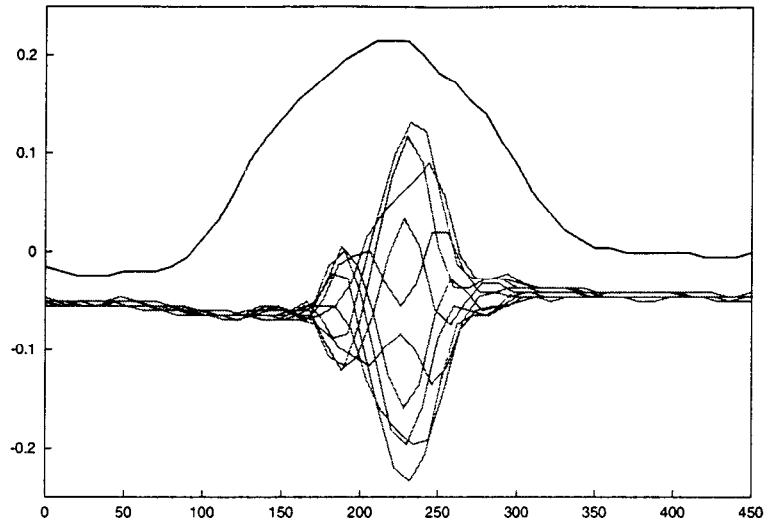


FIGURE 6. Bunch shape (top) and vertical modulation of a high intensity bunch at AGS injection energy of 1.9 GeV during a single bunch head-tail instability. The vertical scale is in arbitrary units and the horizontal scale is in ns.

losses during the 0.4 second storage time in the AGS, and about 3 percent is lost at transition (8 GeV). Although activation levels are quite high all machines can still be manually maintained and repaired in a safe manner.

HIGH INTENSITY OPERATION FOR FAST-EXTRACTED BEAM

During fast-extracted beam operation single bunches are extracted multiple times from the AGS at 24 GeV. The bunch length at extraction has to be as short as possible. This requirement conflicts with the effort to dilute the beam to stabilize it at high intensity. In particular, without additional bunch dilution after transition crossing, fast transverse single bunch instabilities develop leading to beam loss or beam blow-up. A technique to shorten the bunches before extraction was developed using adiabatic quadrupole pumping. With this technique a coherent quadrupole excitation as shown on the left side of Fig. 7 could be maintained for the multiple extractions [5]. To further shorten the bunches and also to limit the amount of beam per single extraction to less than the target station limit of 7×10^{12} protons the six bunches were adiabatically split into twelve bunches. This is shown on the right side in Fig. 7.

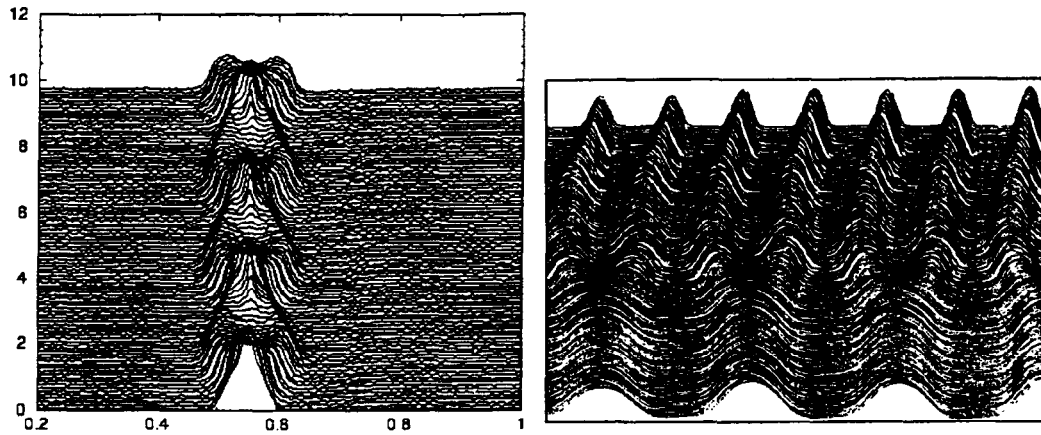


FIGURE 7. Evolution of the shape of a high intensity proton bunch during adiabatic quadrupole excitation (left) and adiabatic bunch splitting (right)

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